Computer-Supported Collaborative Learning
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Learning the physics of electricity: A qualitative analysis of collaborative processes involved in productive failure

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Abstract Earlier quantitative studies in computer-supported collaborative learning identified 'Productive Failure' (Kapur, Cognition and Instruction 26(3):379–424, 2008) as a phenomenon in which students experiencing relative failures in their initial problem-solving efforts subsequently performed better than others who were in a condition not involving an initial failure. In this qualitative study, we examine the problem-solving dynamics of two dyads: a Productive Failure (PF) dyad who initially received a low-structured activity and a Non-Productive Failure (N-PF) dyad who initially received a high-structured activity. Both dyads then received an identical high-structured problem-solving activity. This process was repeated using multiple sets of problems, and this paper will discuss two sets. Interactions of the two dyads were logged. Data for this study included video conversations of the dyads, screen captures of their use of a computer model, and their submitted answers. Results indicated that initial struggle and failed attempts provided an opportunity to the PF dyad to expand their observation space and thus engage deeply with the computer model. Over-scripting proved to be detrimental in creation of a mutual meaning-making space for the N-PF dyad. This paper suggests that the relative success of the PF dyad might be viewed in terms of induction of reflective reasoning practices.

Keywords Collaboration · Electricity · Physics education · Problem solving · Productive failure · Scientific inquiry

Introduction

Earlier quantitative studies (Jacobson et al. 2009; Kapur and Kinzer 2009; Kapur 2008; Pathak et al. 2008) in computer-supported collaborative learning (CSCL) have demonstrat-

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ed the hidden efficacies in low-structured (i.e., no or minimal support for procedures and directions) problem-solving processes, which might provide productive resources in later problem solving. Kapur (2008) set up an experiment in which student triads worked on ill-structured problems (in the domain of mechanics) followed by well-structured problems (i.e., low-to-high structure), whereas the comparison condition involved triads of students who worked on well-structured problems (i.e. high-to-high structure). Each group then received a post-test that included conceptual items as well as an ill-structured problem. It was found that the students in the initial high-structure condition performed poorly on the post-test. In contrast, the students in the low-to-high structure who could not solve the initial ill-structured problem were found to successfully solve the ill-structured problem on the post-test and they were able to perform better on conceptual items on the post-test. Kapur (2008) refers to this phenomenon as *Productive Failure* (PF).

A study conducted by the authors of this paper (Pathak et al. 2008; Jacobson et al. 2009) in the domain of physics involved problem solving on four topics: Coulomb's Law, Ohm's Law, series circuit, and parallel circuit, mediated by NIELS (NetLogo Investigations in Electromagnetism) models (Sengupta and Wilensky 2007a, b, c, d) initially developed at Northwestern University. The study involved 16 dyads in the productive failure (PF) condition and 16 dyads in non-productive failure (N-PF) condition. The productive failure (PF) group initially received a low-structured activity and a non-productive failure (N-PF) dyad initially received high-structured activity. Both groups then received an identical high-structured problem solving activity. The quantitative findings indicated that the PF group scored significantly higher on the post-test than the non-productive failure (N-PF) comparison group. Overall, these findings are consistent with the results of other studies of productive failure (Kapur 2009, 2010) and with the earlier work of other researchers. For example, research by Schwartz and Bransford (1998) employed the "time for telling" approach that found greater learning associated with an unstructured activity ("time for talking") followed by a lecture ("time for telling") that provided more structure subsequently, in contrast to either initially structured or completely non-structured activities. Research into learning with tutors by VanLehn and associates (2003) has also documented how problem solving impasses in tutoring sessions led to enhanced learning compared to similar tutor-provided feedback in which students had not experienced an impasse in problem solving.

In this paper, we qualitatively examine the problem-solving dynamics of a PF dyad and a comparison condition, N-PF dyad from an earlier study by authors of this paper (Pathak et al. 2008; Jacobson et al. 2009) on two topics: Ohm's Law and parallel circuit. The purpose of this analysis is to gain insight into the learning processes associated with a productive failure learning condition and the learning failure that occurred in the more "canonical" worksheet-oriented problem-solving activity in the N-PF comparison condition.

Participants and procedures

The participants in the study were grade 10 students who were studying for their General Cambridge 'O' level Examination in an all-boys school in Singapore. We recorded the computer screen activities and conversations of six PF and six N-PF groups on four topics amounting to 960 min of video for each group. Considering the completeness of data sources (i.e., some students missing the lessons or that the video was not properly recorded), we intend to base our report on video analysis of 160 min of problem solving activities on two topics—Ohm's Law and parallel circuit. Participants are two dyads: Ben and Ruo from the PF group and Jian and Mick from the N-PF group. Based on the teacher's ratings, Ben and Ruo (PF) was a lower achievement pair than Jian and Mick (N-PF). The data for this study comes from three sources:

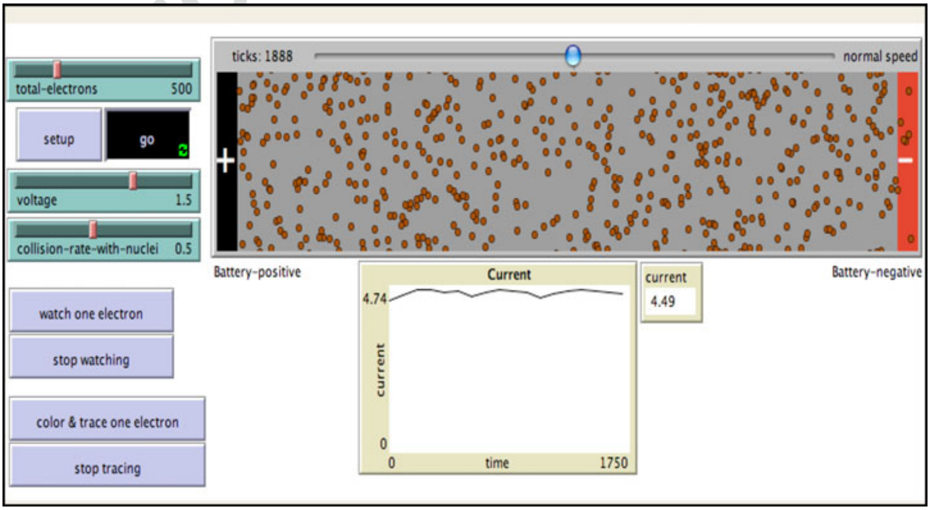
- Video conversation of dyads with each other.
- Paper and pencil solutions to the problems submitted by the dyads.
- Screen capture of the dyads' computer model use.

Materials and learning sequence

This paper focuses on two dyads' problem solving—one in the PF condition and the other in the N-PF condition. Problem solving activities in both conditions were mediated by NIELS. In the following sections, we explain the corresponding NIELS models. The explanation is followed by discussion of conceptualization of activity structures in the PF and N-PF conditions.

Ohm's law NIELS model Figure 1 is a screen shot of the Ohm's Law NIELS model. Students can change variables and observe the effects on the free electron propagation in a wire. The figure shows effects of the application of battery voltage to the ends of a conducting wire. Students can collect quantitative data such as total number of electrons, collision rate with nuclei, and battery voltage (macro-level attributes), and qualitatively observe its effects on electron movement (micro-level phenomenon).

Parallel circuit NIELS model Figure 2 is a screen shot of the NIELS parallel circuit model. It shows two conducting wires joined end to end. Each end is then connected to one end of the battery terminal. The resulting circuit is called a parallel circuit. In the model, students can change the variables, such as resistances in wires, battery voltage and gather quantitative data, such as the current in each wire and the voltage across each wire (macro-level attributes) and can qualitatively observe the resulting change in free electron movement in two wires (micro-level phenomenon).



Q5

Fig. 1 NIELS model of Ohm's law

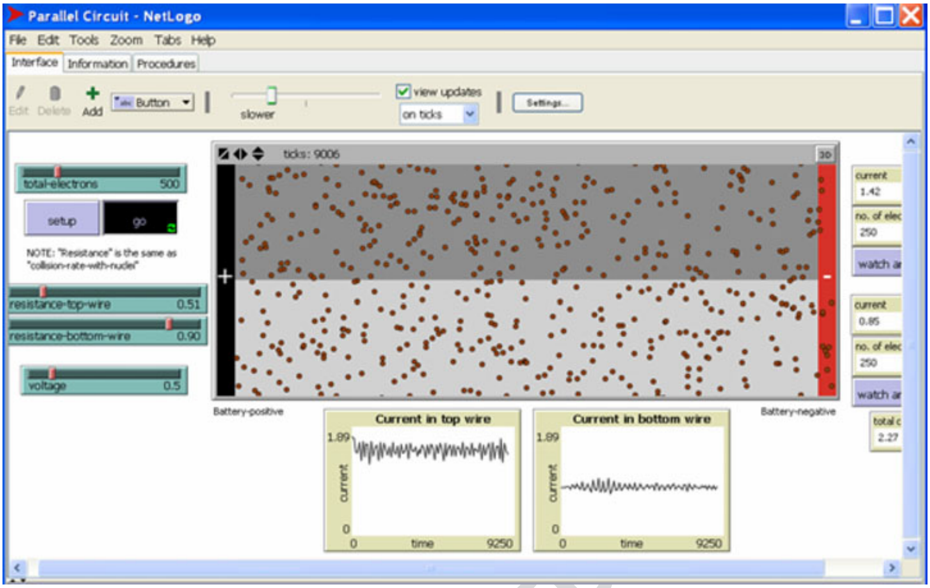


Fig. 2 NIELS model of parallel circuit

Specific problems testing key concepts in the targeted topics were developed. The problems were discussed with the teachers before implementation. The PF dyad initially engaged in a low-structured problem-solving activity while the N-PF dyad was initially given a high-structured problem-solving activity. Both dyads then received identical (high-structured) problems to solve. Only Activity one was structurally different for two dyads. Activity two was identical for both dyads. Table 1 shows the sequencing of the activities for PF and N-PF dyads. Each activity lasted 20 min. Thus, each problem solving sequence for a topic was completed in 40 min.

We present below our conceptualization of Activity one and Activity two.

Activity one (N-PF): This problem-solving activity was directed at understanding an effect of a variable on the movement of free electrons. The structure in this activity was provided in a tabular form resembling a canonical work sheet structure.

This work is based on the concept of one-to-one correspondence (Bittinger and Davic 2001). One-to-one correspondence refers to situations where each element of a variable set can be matched with each element of another set, making sure of a complete mapping among elements of the variable sets. For example, as shown in Table 2, the dyad was provided with independent and dependent variables and the number of readings (elements) that need to be taken to identify the relationship between the variables. Here N-PF students can easily find the correspondences

Table 1 Problem solving activity sequence

	Activity1 (20 min)	Activity 2 (20 min)
PF	Low structure	High structure
N-PF	High structure	High structure

Table 2 Relationship between collision rate and current

Collision rate with nuclei	Time taken to reach battery negative to battery positive	Current
0.5		
0.7		
1.0		

between the elements of one set and the other set by experiments with the NIELS. The activity ended with problems that students were expected to answer. (Table 3)

Activity one (PF): The PF dyad was provided with a problem identical to the one provided to the N-PF dyad without an imposed structure. Here the PF dyad was expected to decide the independent and dependent variables as well as to seek out the correspondences between the elements of various variable sets they created. It was expected that the students would first struggle to find dependent and independent variables to make predictions and observe the behavior of the model in the animated visualization and the graphical output.

Activity two (N-PF and PF): This structured activity focused on realizing the importance and effect of a variable in Ohm's Law. Both PF and N-PF dyads received the same problem. It was structurally similar to the Activity one for the N-PF dyad.

Analytical approach

Although inquiry and problem solving have been considered independent approaches in the past literature (See Zimmerman 2000), current approaches indicate a slant towards integrative investigation. Descriptive frameworks for an integrative approach have been developed combining problem solving with inquiry (Klahr 2000; Klahr and Dunbar 1988). This combination integrates concept formation with reasoning. As Chin and Malhotra (2002) indicate, authentic scientific inquiry is closely linked with reasoning. With an aim to create a more comprehensive view of problem solving, our analysis is based on an

Table 3 Scientific inquiry engagement indicators

Indicators	Abbreviation	Definition
Generation of predictions	GP	Students make educated guesses on possible outcomes of problem solving.
Design of experiments	DE	Students design experiments with the NetLogo electricity models for electricity require the crucial aspects of scientific experimentation, for instance; convert the question/predictions into measurable attributes.
Execution of experiments	EE	Students collect data accurately in presentable and analyzable formats.
Experiment-based inference of relationships	EIR	Students look for relationships among variables and patterns, and their representations.
Model-enabled reasoning	MER	Students express interrelationship between time, distance and/or speed of electron movement (i.e. micro-level phenomenon) and their emergent manifestations; current and resistance (i.e. macro attributes).

integrative view of inquiry and problem solving. We describe our process of analyzing the scientific inquiry of two dyads below.

Content logs and transcription: The dyads' video-recorded conversations were transcribed with time stamps. Two members of the research team watched the process videos along with transcriptions and jointly identified distinct interaction events in each problem solving activity. This helped create 'content logs' (Jordan and Henderson 1995) of events in each problem-solving activity. Although at times two or more interaction events overlapped (e.g., use of model overlapped with conversations or paper-and-pencil work overlapped with conversations), an attempt was made to present each content log with a distinct interaction event (see Tables 4, 5, 6 and 7). The activity also required dyads to produce an answer on paper. The paper-and-pencil work was considered a distinct interaction event.

t4.1 **Table 4** Jian and Mick's interactions on Ohm's Law

Event	i	Time	Response	Engaged in
A. Problem solving activity 1-working with variables		Time on task- from 2:19 to 12:21	Collision rate with nuclei / Time taken to reach battery negative to battery positive / Current 0.5 / *(4.28+ 4. 06) ÷2 = 4.11* / *1.19* 0.7 / *(6.57 + 6.34) ÷2 = 6.46* / *0.87* 1.0 / *(9.17+ 8.72) ÷ 2 = 8.95* / *0.7*	EE
B. Problem solving activity 1-Discussion		3:59 4:01 4:05 4:10 4:23 4:44 5:10 5:39	1. Jian: 0.5, 0.7, 1, 2, 3 (Reading current window) 2. Mick: Ah? Already stopped? Play again. (Stick his head forward to look at the screen, then peeps at Jian's handout). 3. Jian: 1, 2, 3, 4… 1.5, go to 1.6… "Take a stopwatch and measure the time taken by the electron" (Reading instructions) 4. Mick: 1.77 plus 1.5 divided by 2? *5.* Jian: Take average? *6.* Mick: Back again(Looking at the screen) *7.* Jian: Let's see what current is (Peeps at Mick's handout) *8.* Jian: 1, 2, 3 go. (Jian intensely looking at the screen)	EE
C. Problem solving activity 1-solution			Q. How would you describe effect of collisions on current? Why is it so? *Answer: As the collision rate increases, the current in ampere decreases. The collision rate is inversely related to the current.*	EIR MER
D. Problem solving activity 2-Discussion		21:51 24:35 25:53 27:01 27:10 27:24 27:27 27:49 28:01 28:10	9. Jian: 1.26 (reading current value)… 1.3, I am not sure about average. 10. (They re-run the model with same parameters to get the current value and seen writing on the worksheet) 11. Jian: 1.0, (referring to voltage value) ready? 2.45 (Observing closely)… 2.63+2.45 divided by 2. (writing down the value on his handout) 12. Jian: You do it…we manipulate the equation (Not in camera sight) 13. Jian: According to Ohm's law… "Why is it so?" (Reading from the worksheet) … according to Ohm's law, it states that RI=V, right?(asking Mick, looking at Mick) 14. Mick: Yes, RI=V 15. Jian: Hence we can reach that conclusion… current goes up, you see… 16. Mick: We still can make that conclusion. (Smiling and looking at Jian's handout) 17. Mick: Oh… 18. Jian: Show it is I=V over R… Manipulate it.	EE EIR
E. Problem solving activity 2-solution			Q. How are the three values of current related to voltage? Why is it so? *Answer: The higher the voltage, the greater is the current.*	EIR

Table 5 Jian and Mick's interactions on parallel circuit

<table>
<tr><th>Event</th><th>Time</th><th>Response</th><th>Engaged in</th></tr>
<tr><td>A. Problem solving activity 1- working with variables</td><td>Part a. Time on task- from 4:37 to 13:00
Part b. Time on task- from 13:10 to 15:12</td><td><table>
<tr><th></th><th>Settings</th><th>Voltage</th><th>Top wire current</th><th>Bottom wire current</th></tr>
<tr><td>Part a</td><td>N=300, R1=0.5, R2= 0.5</td><td>0.5
1.0
1.5</td><td>0.89
1.84
2.62</td><td>0.87
1.85
2.64</td></tr>
<tr><td>Part b</td><td>N=300, R1=1.0, R2= 0.5</td><td>0.5
1.0
1.5</td><td>0.89
1.84
1.35</td><td>0.87
1.85
2.71</td></tr>
</table></td><td>EE</td></tr>
<tr><td>B. Problem solving activity 1- discussion</td><td>7:03
7:34
9:29
18:07
18:20
18:29
18:30
18:39
18:41</td><td>1. Mick: 0.5 (Raising his hand to gain attention from teacher after reading out the value)
2. Jian: No, I don't think so, 0.2… it's in between (Raising his hand to gain attention from teacher)
3. Jian: Do I need to be exact? (Pointing at graph, to teacher)
4. Teacher: Did you write anything about voltage? (Asking Jian)
5. Jian: Higher the voltage higher the current, it's about ohm's law… directly related (Looking at teacher)
6. Teacher: So you are using ohm's law?
7. Jian: Yes.
8. Teacher: Ok, plays…but there are two variables. (Talking to Jian, Jian looking at teacher)
9. Jian: You write about them…</td><td>EE
EIR</td></tr>
<tr><td>C. Problem solving activity 1- solution</td><td></td><td>Q. What is your observation about current in both the wires? Explain why it is so.
Answer: The current in the top wire is half the current in the bottom wire us the resistance of top wire is twice that of the bottom. The higher the resistance, the lesser is the current flowing through.</td><td>EIR</td></tr>
<tr><td>D. Discussion on problem solving activity 2</td><td>25:25
25:45
26:46
27:10
27:25
27:46
29:13</td><td>10. Jian: 1.0 (Writing in handout)
11. Jian: This is top wire … it is 0.82, 0.83 (Looking at computer screen)
12. Mick: Take average (Pointing at graph)
13. Jian: Bottom wire is 0.5? (Asking Mick)
14. Jian: Time is … measure? (Looking at handout)
15. Mick: 5.14
16. Mick: Finish?</td><td>EE</td></tr>
<tr><td>E. Problem solving activity 2- Solution</td><td></td><td>Q. Explain even if the charges are same why the current is different in both the wires.
Answer: The current in both the wires depend on the collision rate wire nuclei in both wires. The higher the collision rate, the higher the resistance in the wires.</td><td>EIR</td></tr>
<tr><td>F. Post solution</td><td>40:33</td><td>17. Jian: Can't tell why, due to collisions? Cannot explain why (Talking to teacher, as he was handing over and showing worksheet)… Cannot explain…</td><td></td></tr>
</table>

An important issue was interactions of dyads with the computer models. Dyads explorations of model use with variable settings, proved to be complex for presentation in this paper. The challenge was in the presentation of interactions with model settings. It was finally decided to present such interaction events in the form of a Table (See Table 6-A and 7-A) and is presented as a distinct event.

Design of coding scheme: Development of a coding scheme for identifying instances of authentic scientific inquiry (or lack thereof) for this project was challenged by two crucial questions: (a) How can we describe the rich context of learning processes using a set of indicators and (b) What would be an appropriate set of indicators that would constitute the components of integrative inquiry in a collaborative computer environment?

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t6.1 **Table 6** Ben and Ruo's interactions on Ohm's Law

<table>
<tr><th>Event</th><th>Time</th><th>Responses</th><th>Engaged in</th></tr>
<tr><td>A. Problem solving activity 1-working with variables</td><td>Time on task- from 00:00 to 7:06</td><td><table>
<tr><td>No of electrons</td><td>Voltage</td><td>Collisionrate</td></tr>
<tr><td>500</td><td>1.5</td><td>0.5, 0.8</td></tr>
<tr><td>500</td><td>0.5</td><td>0.7, 0.2, 1.0, 0.1</td></tr>
<tr><td>2000</td><td>0.5</td><td>0.1</td></tr>
<tr><td>5</td><td>0.5</td><td>1.0</td></tr>
<tr><td>1120</td><td>0.5</td><td>0.1</td></tr>
</table></td><td>DE
EE</td></tr>
<tr><td>B. Problem solving activity 1-Discussion</td><td>5:29

6:00

6:08
7:45

7:50
7:54
8:12

8:35</td><td>1. Ruo: It goes down, see, you cannot say that the current will go down, what I will write is, when collision rate increase… you can very steadily say that current goes down from 7.26 to 2.26.(Looking at screen, talking to Ben)
2. Ben: Current is more constant when collision rate is stable.(looking down, explaining to Ruo)
3. Ruo: Why it is low?(Looking at screen, asking Ben)
4. Ben: It's because when electrons collide, current drops. No idea. When you notice this less particle thing, it goes up, when there are more electrons colliding, it goes down. (moving his head close to screen, talking to Ruo)
5. Ruo: So when electrons collide…(Focusing on screen)
6. Ben: Current drops.
7. Ruo: The current falls… (Writing) "How would you…" (Reading the question) So you just need to explain why it falls? Or you need to explain why it collides?
8. Ben: Yeah… why it collides and falls…No idea. (Not in camera view)</td><td>EIR
MER</td></tr>
<tr><td>C. Problem solving activity 1-Using information</td><td>9:22

9:43

14:19</td><td>9. Ruo: Collision rate in a wire causes resistance…(Reading from "How to use it")
10. Ben: Due to resistance… I am done, I am done. (Not in camera view)
11. Ruo: When collision of nuclei is so little, when there are a lot of electrons as to there is little electron, the lesser the electron, more the current… Is it because they don't repel each other, so they move faster? (Seems talking to himself, adjust voltage and collision rate)</td><td>MER</td></tr>
<tr><td>D. Problem solving activity 1-Solution</td><td></td><td>Q. How would you describe effect of collisions on current? Why is it so?
Answer: The current is more constant when the collision rate is low. When the electrons collide, the current drops due to resistance. When there is, lets say, a numbers of about 10 electrons colliding with the nuclei at one time, the current drops by a lot. However, when there is only about one or two particles colliding with the nuclei at one, the current barely falls or the drop the current is negligible as observed from the model. When collision rate is low, there is less resistance, thus, more current.</td><td>MER</td></tr>
<tr><td>E. Problem solving activity 2-Discussion</td><td>23:00

23:08

23:17

23:20

23:22
23:28</td><td>12. Ben: "How's the value of current related to voltage? Why is it so?" (Reading from worksheet)… Ok, as the voltage increases (Writing on worksheet), the time taken...
13. Ruo: How are the three values related to voltage? (Reading from handout)
14. Ben: Want to use this one? (Pointing to stop watch, asking Ruo)
15. Ruo: Try, try. Let's check time.(Used mouse and clicked the "go" button)
16. Ben: Try this one. (Referring to the current model setting)
17. Ruo: It's not totally to know… (Watching the model together with same parameters)</td><td>DE
EE
EIR</td></tr>
<tr><td>F. Problem solving activity 2-Solution</td><td></td><td>Q. How are the three values of current related to voltage? Why is it so?
Answer: As the voltage increases, the current increases. When the voltage increases the time taken for the electrons to reach battery negative to battery positive decreases and as the collision rate with nuclei is constant and as the velocity so the electrons increases and as V = RI and thus current increases as the role of collision remains constant.</td><td>MER
EIR</td></tr>
</table>

> In this context, the work of White and Frederickson (1998) proved significant. They emphasized the explanatory role of computer models in scientific inquiry and their affordances for problem solving. They propose five components in their inquiry cycle: Question, Generation of predictions, Design of experiments, Experiment based inference of relationships, and Apply.

Further, following Chinn and Malhotra (2002), we attempted to look for the design of experiment in terms of two aspects:

1. Limiting the predictors in the exploration space: This investigation includes issues such as—how do students convert the predictions into independent and dependent variables?
2. Collecting the data in analyzable format: This investigation included issues such as—do students make a distinction between number of collisions and collision rate while conducting experiments? Do students distinguish between the number of electrons that move and rate of movement of electrons?

The components of inquiry, namely *Question* and *Apply* were less relevant for our purposes. First, researchers designed the problems (or Questions according to White and Frederiksen (1998)). Second, we were interested in monitoring the model-enabled reasoning to differentiate reasoning with micro–macro level concept formation (Wilensky and Resnick 1999) from reasoning with prior knowledge (for instance, use of mathematical equations for Ohm's Law). This led us to add the component of model-enabled reasoning to our coding scheme. Figure 3 provides a schematic of model-enabled reasoning based on the detailed qualitative and mathematical treatment of electron conduction in metal (e. g. Purcell 1985; Ashcoft and Mermin 1976). Various arrows in the figure indicate what engagement on model-enabled reasoning might entail.

By adopting and later expanding the approach of White and Frederiksen (1998) model of an inquiry cycle, we devised a coding scheme that fits our research. Although we do not argue that the five indicators in our coding scheme are mutually exclusive, we do believe that they provide an appropriate working framework. The five indicators and their explanations are provided in Table 3.

Coding Two researchers—one with a background in the learning sciences and technology and the other with a background in physics—coded the selected events for students' engagement in components of inquiry. These researchers were involved from the inception of the project to the writing of findings. Employing two researchers from diverse research backgrounds ensured a form of triangulation (Denzin 1978) in interpretations of inquiry as an interaction event. It was found that differences in understanding between the coders helped promote a better understanding of how the dyads were engaged in various components of inquiry. After independently coding the transcripts, differences were resolved by joint discussion to reach a consensus on the coding of interaction events.

Results

In this section, we report on the dyads' interactions over two sets of problem-solving activities. The first set of activities concerns Ohm's Law while the second set of activities concerns parallel circuit. In the following sections, we describe interactions of the N-PF dyad (Jian and Mick) followed by interactions of the PF dyad (Ben and Ruo). The discussion refers to Tables 4, 5, 6, and 7. The dyad's paper-and-pencil work and interactions t7.1 **Table 7** Ben and Ruo's interactions on parallel circuit

<table>
<tr><th>Event</th><th>Time</th><th>Responses</th><th>Engaged in</th></tr>
<tr><td>A. Problem solving activity 1- working with variables</td><td>Time on task- from 00:40 to 8:02</td><td><table><tr><th>No of electrons</th><th>Voltage</th><th>Collision rate R1</th><th>Collision rate R2</th></tr><tr><td>500</td><td>1.0</td><td>0.5</td><td>0.5</td></tr><tr><td></td><td>0.5</td><td>0.45</td><td>0.9</td></tr><tr><td></td><td>0.5</td><td>0.45</td><td>0.45</td></tr><tr><td></td><td>1.0</td><td>0.45</td><td>0.45</td></tr></table></td><td>DE
EE</td></tr>
<tr><td>B. Problem solving activity 1- Discussion</td><td>1:02
1:08
2:15
3:29
3:30
3:31
7:50
7:56
7:58
8:01
8:05
8:11</td><td>1. Ben: So funny one. Current at the top is same as current at the bottom. Number of electrons is same. (Watches changes in the graph)
2. Ruo: It's collision rate, it's still… "What is your observation about current in both the wires? Explain why it is so" (Reading the question from worksheet)
3. Ben: Change to what? (Controlling the mouse, talking to Ruo)
4. Ruo: Half of it. (Talking to Ruo)
5. Ben: It's about half. (Reaction after changing the resistance, looking at the screen.)
6. Ruo: Because collision rate is about two times. (Explaining to Ben, looking at screen)
7. Ben: I will change R2=0.90. (Running the model with new parameter setting)
8. Ruo: 300, (Reading from counter) it will be equally divided.(Talking to Ben)
9. Ben: Then why that time, we did (referring to series cicuit NIELS model where no of electrons change in two wires)…(Pondering and asking Ruo, placing his left hand in front of his mouth)
10. Ruo: Different model. (Explaining to Ruo)
11. Ben: There must be logic behind. (Still pondering, looking at Ruo)
12. Ruo: This is upper and lower wire, its different one. (Looking at screen)</td><td>DE
EE
EIR</td></tr>
<tr><td>C. Problem solving activity 1- Using information</td><td>13:39
14:54</td><td>13. Ben: What do they write, about voltage? (Scrolling down) Potential difference (reading from screen) "…press 'TRACE and WATCH" a single electron button…" (reading Q 2 from worksheet) (Ben is watching single electron.)
14. Ben: When they have same resistance, they have same velocity. (They used stopwatch to count the time to prove their point)</td><td>EIR
MER</td></tr>
<tr><td>D. Problem solving activity 1- Solution</td><td></td><td>Q. What is your observation about current in both the wires? Explain why it is so.
Answer: When the resistance in both wire are the same, the current in both wire are almost equal. As there are same number of electrons with same resistance both wires, they will have the same current. When the resistance in one wire is half of the other wire, the current in this wire is about two times the other wire; both have the same number of electrons, with equal voltage. The wire with half the resistance compared to the other will have two times the current compact to the other wire, wire, as the electrons have move about two times faster than that of the other wire.</td><td>EIR
MER</td></tr>
<tr><td>E. Problem solving activity 2- Discussion</td><td>33:52
34:10
34:45
34:55
35:02
35:06
35:34</td><td>15. Ruo: Explain why… (Reading the question from worksheet)… Charges are electrons … generally electrons (Talking to Ben)
16. Ben: Isn't it about the same thing? Because of collision rate right?(talking to Rou, looking at the screen)
17. Ruo: Ok… "explain even if the charges are same why current is different" (Reading the question from worksheet again)
18. Ben: Due to collision rate.(Putting his pen to mouth, talking to Ruo)
19. Ruo: Are you sure, it's due to collision rate? Everything goes with V=RI(telling Ben)
20. Ben: Yes, the whole essay is about ohm's law.(Telling Ruo, looking at Ruo)
21. Ruo: I am going to plug in this thing because everything revolves around this explanation V=RI. (Writing on handout)</td><td>EIR
MER</td></tr>
</table>

Table 7 (continued)

F. Problem solving activity 2-Solution		Q. Explain even if the charges are same why the current is different in both the wires. *Answer: Despite number is electrons being the same, the current is determined by the equation V = IR, thus voltage and resistance also affect the value of the current thus even if both charges are the same. If the voltage and resistance is different the current would not be the same.*	EIR MER
G. Post solution	36:36	22. Ruo: you got pencil? I tell you why, if the value of I let's say is 2, and R let's say 7, then how? (Apparently writing on paper, not in view of camera)	
	42:32	23. Ben: when I=2 and voltage is same then resistance is lower, thus what you can say is increase in R is drop in current, it is the "balance". (Look up occasionally at Ruo)	

with model settings reconstructed from the video are indicated in italics. Tables 4 and 5 show the interactions of the N-PF dyad, while Tables 6 and 7 show the interactions of the PF dyad. Dyads' verbal interactions have been minimally edited. The tables also include marked codes for engagement in scientific inquiry.

Interactions of N-PF dyad: Jian and Mick

Jian and Mick seem to focus on getting their measurements correct based on the guidance provided. They mainly reasoned about the observed relationship among variables based on their prior knowledge of mathematical equations for Ohm's Law. We provide below detailed descriptions of their interactions.

Ohm's law The activity in Table 4-A represents work of this dyad on the Ohm's Law NIELS model. The dyad takes each measurement twice and calculates the average. A

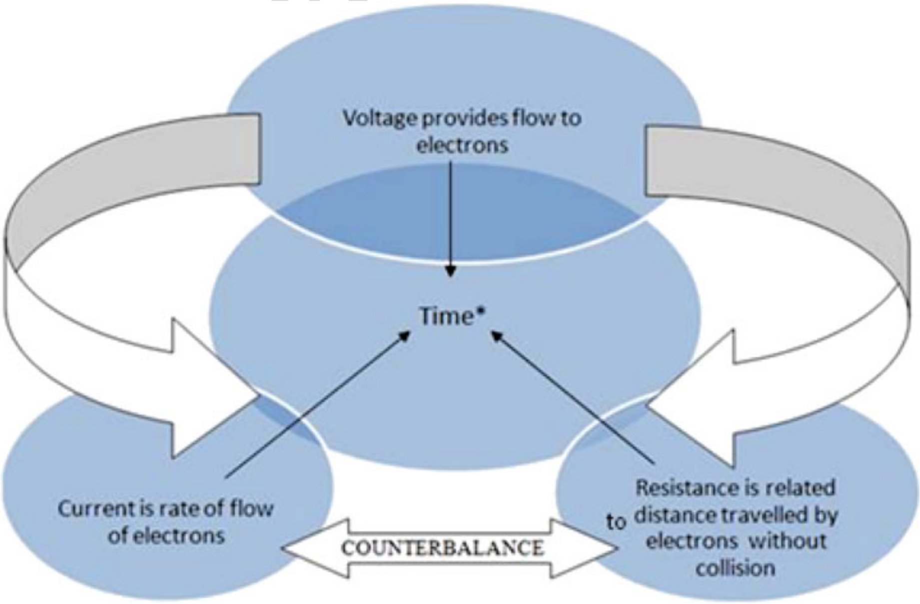

Fig. 3 A schematic representation of model-enabled reasoning. *Time can be interpreted in terms of distance travelled by electrons or speed of electrons

tabular structure is provided to the dyad and they fill in missing values: that is, they engaged in execution of experiments (EE). The missing values filled in by the dyad are indicated in italics. Table 4-B presents part of a conversational episode that took place. The dyad is focused on getting exact values for quantities (Turns #1–6) in response to the task they were asked to carry out. They collect quantitative data on values of electric current (Turn # 7). The conversation is centered on procedural talk about filling in the data (engaged in EE). Here, Jian and Mick have successfully executed the experiment (Table 4-A) that was given and provided a qualitative relationship (Table 4-C), that is they were engaged in experiment-based inference of relationships (EIR) among the macro attributes. The overall engagement with the model is limited to the experimentation scope provided by the structure. Although Jian is observed intensely looking (Turn # 8) at the model, we assume that he is looking at the phenomenon. The scripts do not mention any verbalization of interrelated micro–macro level relationship. During working on Activity 2, Jian and Mick are focused on measurement and accuracy (Turns # 9–12 in Table 4-D). They are trying to arrive at a conclusion (EIR) (See Table 4-D). Even after an apparent conflict about the appropriateness of mathematical form of Ohm's Law (Turn # 13), Jian and Mick are still engaged in manipulation of Ohm's Law (Turns # 15–18). They make an attempt to provide inferences based on Ohm's Law equation (EIR) (Table 4-E) but do not engage in establishing macro-micro relationships. Neither their solution nor their conversations show engagement with model-enabled reasoning (MER).

Parallel circuit The students received a structured activity as shown in Table 5-A (students' answers are given in italics). Their interaction patterns (Table 5-B) appear quite similar for the topic, Ohms' Law, which focuses on quantitative data collection and in establishing a relationship between voltage and current (macro attributes) (EE). This dyad is concerned about getting accurate reading of current shown on the counter (Turn #3). When asked about voltage (Table 5-B, Turn # 4), Jian mentions (Turn #5) Ohm's Law. Their paper-and-pencil solution (Table 5-C) indicates that they are engaged in inferring the relationship among macro-level attributes. They validate their data based on the mathematical form of Ohm's Law (EIR). We do not see them noticing difference in currents in two wires when R1 and R2 have the same values and when R1 and R2 have different values. Here we see the teacher prompting Jian and Mick about the two variables involved (Turn #8).

In the follow-up activity, (Table 5-D, Turns # 10–16) Jian and Mick show engagement in measurement activities (EE). Besides being engaged in validating Ohm's law in parallel circuit, the scripts do not indicate their understanding of the model and its purpose that is, about generating an understanding of electron flow in wires. They are not able to reason about *rate of electron movement* (which includes number of electrons as well as time) that is implied in understanding of current (See Table 5-E). Jian, in his post-solution diction (Table 5-F, Turn #10) expresses helplessness, as he is not able to provide reasoning for the difference in the currents in two wires.

Interaction of PF dyad: Ben and Ruo

The responses on low-structured activity indicate that Ben and Ruo struggled to understand what the representations might mean in the context of experiments. However, they deepened their understanding through interaction with NIELS models and with each other. Ben and Ruo stand in sharp contrast to Jian and Mick who are consistent in their successes in executing and exacting measurements. Below we provide a detailed description of their interactions.

Ohm's law Table 6-A presents video analysis related to working with the model (indicated in italics) in the low-structured activity. The dyad worked with macro attributes of the model such as number of electrons, voltage, and collision rate. This exploration suggests that Ben and Ruo are in the process of testing how higher voltage or more electrons affect current (DE and EE) in a much more unplanned and random manner than was observed in the N-PF group.

As can be seen in Table 6-B, Ruo and Ben focus on two instances of the graph (Turns #1 & 2)—when current drops and when the current is stable (not fluctuating). In general, Ruo focuses on the instantaneous non-linearity in the graph, whereas Ben is looking at the overall nature of the graph (Refer to Fig. 4). Though they try to relate the graphical information to the question asked (Turns #3–7), they are unsure of which observation deployment would be appropriate to answer the question. Both of them seem to be dissatisfied with their observations and tentative inferences. Although they are not entirely sure about the problem question, Ben paraphrases (Turn #8) the question using "and".

Unlike Jian and Mick, Ben and Ruo look for some guidance by scrolling down to the *How to use it* information given in the model (See Fig. 4). Ben associates collision rate, which he was discussing earlier (Turn #2), with "resistance" (Table 6-C, Turn #10). Ruo, on the other hand, seems to be trying to understand the effect of electron collision on current. Ruo wonders if the lack of repulsion between electrons causes faster movement (Turn #11). In addition to the random exploration of the model, the main struggle during this activity for Ben and Ruo is in understanding what the different representations mean. For example, when they change the number of electrons, they do not know that in real experiments, it is similar to replacing the conducting wire with a different material. They are also unable to attribute their observation of collisions to an experimentally measurable form, such as collision rate (failure in the form of understanding the deeper form experimentation techniques/methods, measurements, i.e., failed in EE). However they seem to engage with the graph and use it to draw inferences. They attempt to provide reasoning (MER) for the problem (See Table 6-D). Working on Activity 2, Ben starts reading the problem question

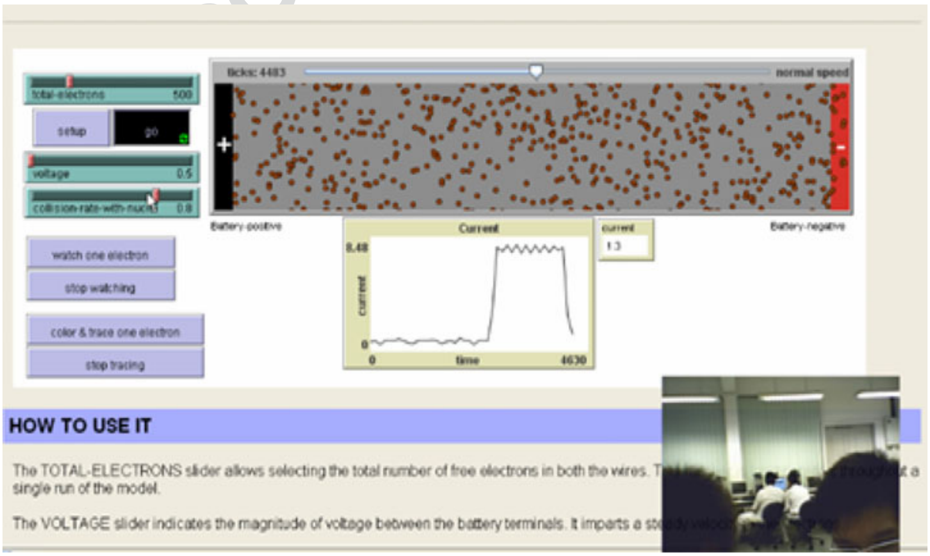

Fig. 4 Ben and Ruo focusing on the nature of graph

before going through the structured activity (Table 6-E, Turn #12). Ruo, on the other hand, tries to understand the relationships (Turn #13) among the variables provided in the structured activity. They decide to engage in experimentation (Turns #14–16) (EE). At the same time, Ruo seems to be saying that the problem solution (Turn #17) lies in reasoning to understand the findings rather than engaging in experiments. Unlike responses to the first problem question, Ben and Ruo are better able to articulate relationships at macro-micro (Table 6-F). For example, they mention the time required for an electron to travel a particular distance. Thus, they based their responses on understanding the dynamic nature of electron propagation; as well as providing a validation to the observation using prior knowledge of Ohm's Law.

Parallel circuit Table 7-A indicates variable settings (indicated in italics) used by students during the low-structured activity. Further, the settings indicate that Ben and Ruo were engaged in understanding critical variables used in determining the critical number of settings needed to arrive at a functional relationship between variables (engaged in DE and EE). Their conversation indicates that they are trying to understand how a change in voltage would affect the current in wires. (Table 7-A, Turns # 1–6). It is important to note that Ben and Ruo are working with the two variables—collision rate R1 and collision rate R2—in a systematically planned manner when compared with their unplanned exploration in the Ohm's Law topic. Ben observes that current and number of electrons in both wires (top wire and bottom wire) is the same (Table 7-B, Turn #1). Ruo immediately ascribes (the same) collision rate as the cause (Table 7-B, Turn #2). In order to explore the phenomenon, Ben decides to change the collision rate in one wire (Turn # 7). Ruo reads the number of electrons from the counter and mentions that current is reduced to half. (Table 7-B, Turn # 8). Ben is puzzled by this observation (Table 7-B, Turns #9, 11) and attempts a comparison with a series circuit. (In a series circuit, current in two wires remains the same, irrespective of their resistances; but electrons in two wires are not the same when the two wires have different resistances.) Ruo then offers help in solving this puzzle by relating it to the pattern in which wires are joined (Table 7-B, Turns # 10, 12). Now, Ben watches the movement of a single electron. However, they cannot explain the voltage effect (Table 7-D, Turn #13) for the observed phenomenon. It is significant that Ben is trying to understand why the same velocity (of electrons) is the reason (for the same currents) when they have the same (resistance) collision rate (MER) (Turn #14).

Ben then concludes that when the resistances are the same, electrons in the two wires have the same velocity (Table 7-C, Turn #14). As seen in Table 7-D, they have deduced the solution to the problem. The answer starts with an experimental observation of the relationship to the rate of movement of electrons, factored again with the number of electrons and time. While working on a follow-up structured activity, Ben wonders (Turn #16) about the question. He thinks he has already answered it. It appears that Ben did not need this canonically structured activity. Ruo clarifies (Turn #17) the questions, but later agrees (Turn #19) with Ben that they know the answer. He concludes that the currents in the two wires still follow Ohm's Law. Ben supports this conclusion (Table 7-E, Turn #20) (MER). While working on this activity, the dyad has figured out that both R1 and R2 *together* determine the current in any single wire. They determine that besides the number of electrons, voltage and resistance also impact the current flowing in a wire (Table 7-F). It is interesting to see Ben and Ruo engaging in post-solution conversation (Table 7-G, Turns # 22–23). Ruo now creates a scenario where current (I) and resistance (R) are considered as two different variables in their prior knowledge of mathematical form of Ohm's Law and wonders about the significance. Ben adds that current and resistance are interrelated ("balance") (Turn # 23).

Summary and conclusion

While studying the collaboration processes in the context of productive we attempted to discuss how these processes unfold in learning environments over time. There is also a need to open up the black box of interactional processes and student artifacts during learning (American Association for the Advancement of Science 1993). Research has shown that students do not spontaneously develop hypothesis and arguments (e. g., Basili and Sanford 1991; Roth and Roychoudhury 1992). Although our study is limited in scale, the findings suggest that attention needs to focus on the activity structure and emerging learning. Despite being given the same computer-supported environment and the same problems, the two dyads differed significantly in their performances. Since our research design manipulates structures of activities, the data provides interesting results in the context of the relation between activity structure and dynamics of problem solving. In this section, we shall attempt to put forward two explanations highlighting two different aspects of this relation. Here, we provide an explanation for the varied performances by the two dyads, PF and N-PF.

As seen in the previous section, the N-PF dyad provided with traditional, canonical worksheet oriented activities tested and validated their prior knowledge. They also focused on single aspects of inquiry in most interaction events. They quickly reached a conclusion as can be seen during discussions, signaling an absence of epistemic activity (Chinn and Brewer 1993). However, it is interesting to note that the N-PF dyad was in fact metacognitively aware that they had not constructed an understanding of electricity concepts, as they mentioned after solving the problem. This raises a doubt if the activity structure was overtly dominant (Barron 2003).

The analysis of the performance of the N-PF dyad leads to the following explanation regarding their relative learning failures with each other and with the computer tool:

Explanation 1 Over-scripting is detrimental to the creation of a shared space for meaning making.

Overall, the PF dyad employed clusters of inquiry components during entire sets of problem-solving activities. During Ohm's Law, they conducted their own small experiments often struggling and failing to understand what the representations might mean.. During struggles and failed attempts (refer to Results section for details) in the low-structured activity, the PF dyad tried to deconstruct the problem into elements of the model, such as electrons characterized by velocity, or distance travelled or time taken rather than relying on their prior knowledge of electricity. This initial activation of cognitive resources might have primed them to *receive* the conceptual and representational structure in the follow-up structured activity.

When the low-high structure was iterated in the parallel circuit, we did not find any struggle or failure reflected in PF dyad's model use. On the contrary, we observed 'systematicity' (diSessa and Sherin 1998) in their model use, signaling their comprehension of the way the representations and macro attributes connect with each other. In the follow-up structured activity, we noticed a gradual sophistication in understanding the complexity of electricity phenomena. This occurred when the PF dyad concluded that having a certain number of electrons may not be sufficient to get the same current, but the resistance and voltage are also to be considered: a deep conceptual understanding missing in their earlier interactions. The eventual emergence of systematicity and conceptual sophistication cannot be isolated from reflective reasoning practices (Schwartz et al. 2004) that the dyad exhibited. For example, as evidenced in their conversations, they compared and contrasted the two topics: the series circuit and parallel circuit and connected the underlying phenomenon of electron movement with a third topic—Ohm's Law—without any explicit instruction or demand by the problems. They also evoked a voltage-centered explanation that fits with an expert's reasoning (Heller and Finley 1992). This analysis of the performance of the PF dyad leads to the following explanation regarding their relative learning successes with each other and with the computer tool:

Explanation 2 Iterations of PF structure induces reflective reasoning practices.

The two explanations taken together suggest that a computer-supported learning environment using overtly scripted activities may not produce authentic practices that scientists engage in. On the contrary, computer-supported learning that purposefully develops trajectories of failures and struggles can lead to deeper and more productive understandings of core science concepts. Clearly, more research is needed to understand the particular learning process underlying such a learning environment.

After proposing a productive failure hypothesis (Kapur 2008; Kapur and Kinzer 2009) in a CSCL context in problem solving in mechanics, Kapur's recent work (2009, 2010) has moved to the domain of mathematics and statistics. His quantitative work compares effectiveness of unsupported initial low structure with other learning conditions in a non-CSCL context. As a complement to his research, our paper has reported on micro qualitative analyses in order to gain insights into the processes associated with learning in productive failure structure compared to more structured computer-supported learning activities. Our work suggests viewing learning with PF in terms of generation of reflective reasoning practices.

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